

TECHNICAL AND ECONOMIC FEASIBILITY  
OF  
ENZYME HYDROLYSIS FOR ETHANOL  
PRODUCTION FROM WOOD

Final Report

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## ABSTRACT

Under the sponsorship of the New York State Energy Research and Development Authority (NYSERDA) and the Solar Energy Research Institute (SERI), Arthur D. Little, Inc., examined the feasibility of enzyme hydrolysis for ethanol production from wood. The feasibility study included a plant location in Jefferson County, New York, and the use of deproteinated cheese whey as the substrate for enzyme production. Debarked northern hardwoods were selected as feedstock for the enzyme hydrolysis operation.

The preliminary process engineering design was based on a plant receiving about 450 dry tons of hardwood per day and producing about 5.5 million gallons of denatured ethanol per year. By-products included cogenerated electricity and a protein-rich animal feed.

Total capital investment for the facility was estimated to be \$60.575 million in 1984. Two base case cash flow analyses were carried out, one with NYSERDA input variables and one with SERI input variables. These resulted in required ethanol selling prices of \$3.87 per gallon and \$4.45 per gallon, respectively.

Given the disparity between these predictions and the current actual price of ethanol, it was concluded that the enzyme hydrolysis of wood is not presently economic. Further research and development are also needed to resolve remaining technological uncertainties and establish markets for new products.

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## SUMMARY

### I. INTRODUCTION AND BACKGROUND

The Department of Energy (DOE) has sponsored a number of basic research and development efforts in the area of enzyme hydrolysis. Directed toward understanding process chemistry, refining unit operations, identifying important process parameters, and testing various integrated process concepts, these R&D efforts have resulted in a large body of data and knowledge on the technology. However, with little or no work completed toward a detailed system analysis and true assessment of the technology's viability, DOE is unable to determine whether enzyme hydrolysis processes are sufficiently advanced to warrant transfer to the private sector or whether further R&D efforts are required.

To rectify this uncertainty, the Solar Energy Research Institute (SERI) contracted for three economic feasibility analyses of enzyme hydrolysis processes. This report contains the findings of one of these studies. This particular study was co-sponsored by the New York State Energy Research and Development Authority (NYSERDA).

The process selected for this feasibility analysis is based on the use of debarked northern hardwood chips as the primary hydrolysis feedstock and deproteinated cheese whey as the source of raw material for enzyme production. The use of deproteinated cheese whey as feedstock for enzyme production offers the advantages of high productivity and a relatively easier fermentor operation (as opposed to slurried feedstocks). Fortunately, there are many areas of the United States where cheese whey is available near substantial hardwood resources. The site selected for this feasibility study (Jefferson County, New York) is located in a major dairy shed and near extensive stands of under-utilized hardwoods. It is also located within reasonable distance to major population areas and gasoline markets throughout the Northeast.

### II. FEEDSTOCK AVAILABILITY AND COST ASSESSMENT

Given the preliminary selection of Jefferson County, New York, as the location for the plant, it became necessary early in the study to assess the availability and cost of the various potential plant feedstocks. Any adverse findings related to a

critical raw material (low supply or high cost) would argue for a change in feedstock or plant location.

The feedstocks identified and major findings relevant to their assessment were:

- Deproteinized cheese whey is available for enzyme production in quantities of about 40 million pounds (dry, pure lactose basis) at a 1984 price of \$0.0243 per pound lactose.
- Secondary wood residues such as sawdust, planer shavings, and clean by-product chips are not available in sufficient quantities to supply the proposed facility. Roundwood can be purchased at a 1984 price of \$30/ODT and debarked and chipped at the plant site. Wood costs are expected to experience real price increases over the lifetime of the plant.
- Wastepaper is too costly to be used as a hydrolysis feedstock in the proposed plant.

### III. REGION ASSESSMENT

Jefferson County was found to be an appropriate location for the proposed plant in terms of its proximity to the whey permeate and northern hardwood feedstocks. Within Jefferson County, the City of Watertown was chosen, as the most advantageous plant location, principally because of its transportation network and supporting infrastructure. For purposes of the feasibility analysis, pertinent information was gathered on utility rates, labor rates, tax structure, water availability and quality, environmental regulations, and climate.

### IV. PRODUCT MARKET ANALYSES

The results of price and market assessments for potential products and by-products are:

- Ethanol blends produced from the proposed plant's output would constitute only 1.4% of the current New York State unleaded fuel market. In addition, there is ready access to other states, including Ohio, which has a state tax subsidy.
- A protein feed produced from yeast and mycelia could be produced in amounts equal to 1.3% of the current state market. Its 1984 price is predicted to be \$230/ton, based on historical data for soybean meal (with an adjustment for protein content).
- Pentose molasses is not predicted to be a viable product due to the relatively small market and its potentially bitter taste.
- Cogenerated electricity can be sold to the utility at a rate of \$0.06/kWh.

- Potential production of lignin from the plant equals 25% of the total U.S. specialty market (prices 7-40¢/lb). Until new markets are developed such as phenol replacement in phenol formaldehyde resins, it is assumed that the ligneous residues are burned as boiler fuel.

#### V. PROCESS ENGINEERING DESIGN AND CAPITAL COST ESTIMATE

The selection of unit operations and processing conditions for the enzyme hydrolysis facility was based on the following criteria:

- (1) Compatibility with available feedstocks and regional market conditions;
- (2) Availability of published yields and other performance data which are, wherever possible, reproducible, consistent, and demonstrated at larger-than-laboratory scale; and
- (3) Demonstration of superior performance or other advantages when compared to alternatives.

In other words, the selected process design takes advantage of recent research advances as much as is practical without sacrificing the probable workability and reliability of the plant. When assumptions were necessary, as was often the case, they were based, wherever possible, on experimental data or on reasoned subjective opinions derived from past experience. Hypothetical improvements which have no basis in fact or experimental confirmation were not included in the base case feasibility analysis; however, some of the sensitivity analyses are based on optimistic projections.

General design criteria which were applied virtually throughout the plant were:

- Overdesign in sizing typically ranges from 10% to 20%.
- Total redundancy (100% capacity sparing) of critical service equipment is kept to a minimum; however, considerable partial redundancy is provided by including dual items in parallel, each sized at 55% or 60% of normal throughput.
- The risk of contamination, which is high in certain areas of the enzyme hydrolysis process, is addressed by:
  - Pasteurization of process fluids;
  - Use of 304 or 316 stainless steel for wetted surfaces, so that equipment which does become contaminated can be returned to a clean condition; and

- Provision of clean-in-place systems for fermentors and hydrolysis tanks.

The key aspects of the material balance, or plant size, are:

- Wood consumption -- 75,264 pounds (34,133 kg) per hour, as-received at 50% moisture, or 452 oven-dry tons per day, or 149,023 oven-dry tons per year.
- Deproteinized cheese whey consumption -- 33,183 pounds (15,049 kg) per hour, or 131,405 tons per year, containing 20,000 tons of lactose.
- Ethanol production -- 4,395 pounds (1,993 kg) per hour, or, after denaturing, 5.54 million gallons (20,960 m<sup>3</sup>) per year.
- By-product feed production -- 1,645 pounds (746 kg) per hour at 10% moisture, or 6,514 tons per year.
- Electricity production -- 10.7 MW, or 85 million kwh per year

The plant design includes the following areas:

- Area 100, Wood Receiving, Storage, and Handling, where roundwood (hardwood species only) is received, stored, retrieved, debarked, and chipped. Storage is provided for chips and bark.
- Area 200, Steam Explosion, where the debarked hardwood chips are permeated with steam at 600 psig (42.4 bars), then explosively decompressed in order to destroy the integrity of the lignin-cellulose protective structure, increase the surface area of the substrate, and render the cellulose more susceptible to enzyme attack.
- Area 300, Enzyme Hydrolysis, where the steam-exploded wood is fed at intervals to the enzyme broth (from Area 700) and held at 45-50°C for a period of 72 hours, during which time the cellulose and hemicellulose in the wood are hydrolyzed to hexose and pentose sugars.
- Area 400, Ethanol Fermentation, where the hexose sugars in the clarified hydrolyzate are continuously fermented to ethanol.
- Area 500, Alcohol Recovery, where the product ethanol is distilled from the dilute fermentation beer and dehydrated.
- Area 600, By-product Processing, where the excess yeast (from Area 400) and fungal mycelia (from Area 700) are mixed, dried, and sent to storage for eventual sale as animal feed.
- Area 700, Enzyme Production, where the lactose in deproteinized cheese whey is used as the substrate for fermentation of Trichoderma reesei MCG80 in continuous culture. After fermentation, the excreted enzyme is separated

from the fungal mycelia solids and the clarified enzyme broth is sent to Area 300.

- Area 800, Utilities and Waste Treatment, where organic waste-waters from the process are anaerobically digested to produce methane and then further treated aerobically; where bark, ligneous residues (from Area 300), and methane are burned for steam and electricity generation; and where other required utilities are located.
- Area 900, Materials Storage and Shipping, where product alcohol and feed by-product are stored and loaded out and where gasoline and diesel (needed for denaturing and plant fuel use, respectively) are unloaded and stored.
- Area 1000, Buildings and General Services, which is not a plant area but rather a catch-all category for other required non-process items.

The fixed capital investment for the facility is estimated at \$60,575,000 in 1984, as shown in Table S-1.

## VI. OPERATING REQUIREMENTS AND COSTS

The operating costs of the enzyme hydrolysis facility can be divided into variable and fixed (invariable) contributions. The variable operating requirements, which increase more or less linearly with production rate, include raw materials, chemicals and nutrients, and utilities. Fixed or invariable operating requirements include labor, maintenance materials, general and administrative expense, interest on debt, insurance, taxes, and depreciation. Operating requirements and 1984 unit prices are summarized in Table S-2.

## VII. CASH FLOW ANALYSES

To analyze the profitability of the enzyme hydrolysis plant and to examine the effects of varying process and financial assumptions, a discounted cash flow analysis program was developed. The program is built upon a Lotus® 1-2-3 spreadsheet.

Two "base case" cash flow analyses were performed: one based on a set of standard input variables supplied by SERI and the other based on NYSERDA preferences, New York State data, and costs and projections developed in this study. These are labelled the "SERI base case" and the "NYSERDA base case," respectively. A series of excursions, or sensitivity analyses, were also carried out. The sensitivity analyses were all performed as variations on the NYSERDA base case.

Table S-1. Fixed Capital Investment

Installed Equipment

Area 100	- Wood Receiving, Storage, and Handling	\$3,586,000
Area 200	- Steam Explosion	2,800,000
Area 300	- Enzyme Hydrolysis	8,695,400
Area 400	- Ethanol Fermentation	2,353,000
Area 500	- Alcohol Recovery	2,158,600
Area 600	- By-product Processing	510,000
Area 700	- Enzyme Production	9,343,700
Area 800	- Utilities	
	- Power Plant	13,500,000
	- Anaerobic Digestion and Waste Treatment	3,400,000
	- Gas Engine Generators	1,806,000
	- Other	2,658,000
Area 900	- Materials Storage and Shipping	347,200
Area 1000	- Buildings and General Services	<u>3,728,100</u>

Subtotal - Installed Equipment \$54,886,000

Land 200,000

Contingency @ 10% Installed Equipment 5,489,000

Fixed Capital Investment (FCI) \$60,575,000

Basis: Mid-1984 dollars for Jefferson County, New York, location

Table S-2. Operating Requirements

<u>Variable Costs</u>	<u>Unit</u>	<u>Price 1984</u>	<u>Base Case Annual Usage</u>
Raw Materials:			
Wood	tons	\$15.00	298,045
Lactose	tons	48.60	20,000
Gasoline	gallons	0.80	263,700
Chemical and Nutrients:			
KH <sub>2</sub> PO <sub>4</sub>	tons	1,000	320
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	tons	79	1,120
Urea	tons	200	240
Tween 80	tons	1,460	400
MgSO <sub>4</sub> ·7H <sub>2</sub> O	tons	360	240
CaCl <sub>2</sub>	tons	200	240
FeSO <sub>4</sub> ·7H <sub>2</sub> O	tons	130	4
MnSO <sub>4</sub> ·H <sub>2</sub> O	tons	300	1.2
ZnSO <sub>4</sub> ·H <sub>2</sub> O	tons	540	1.2
CoCl <sub>2</sub>	lbs	2.92	3,200
NH <sub>3</sub> (anh.)	tons	210	180
Antifoam	lbs	0.25	170,000
Other Chemicals			\$482,000
Utilities:			
Electricity	kWh	0.04	41.976 x 10 <sup>6</sup>
Wood Fuel	tons	20	0
Diesel Fuel	gallons	1.00	13,728
<u>Fixed Costs</u>			
Labor:			
Operating	man-years	24,000	61
Foremen	man-years	28,000	21
Supervisors	man-years	34,000	4
Maintenance	man-years	20,000	8
Maintenance Materials			\$1,239,000
General & Administrative Expense			\$700,000
Interest			0
Insurance			0.01 (FCI + WC)
Property Taxes			0.011 FCI
Depreciation			See Section 6.2

The SERI base case resulted in an ethanol selling price of \$4.45 per gallon (\$1.18 per liter), assuming a required 15% internal rate of return. The NYSERDA base case resulted in a price of \$3.87 per gallon (\$1.02 per liter). The various components contributing to the selling price in a typical year of operation are shown in Table S-3.

Of the sensitivity analyses carried out, only the sale of lignin resulted in competitively priced ethanol.

#### VIII. IDENTIFICATION OF RESEARCH PRIORITIES

An important product of this work is the identification of data gaps and associated research needs in the area of enzyme hydrolysis. Resolving the remaining technical uncertainties is necessary for the ultimate commercialization of the technology.

High-priority research needs which were identified are as follows:

- Continuing efforts to reduce the cost of pretreatment are needed.
- The hydrolysis operation has several high-priority research areas. These include:
  - Further development of fed-batch technology;
  - Investigation of reliable aseptic operating techniques;
  - Development of information on dewatering of hydrolyzate residues; and
  - Further examination of the potential for enzyme recycle.
- Further development is needed to better demonstrate continuous enzyme production on soluble substrates.
- Tendencies toward mutant reversion need to be quantified.
- High-value uses of by-products need to be demonstrated and markets developed.

Medium-priority efforts are less crucial, but still important to commercialization and are necessary for successful process scale-up. Areas which contain medium-priority R&D requirements are:

- Washing and dewatering of explosively decompressed wood need to be demonstrated.

Table S-3. Typical-Year Production and  
Capital Recovery Costs

	<u>1984 \$/gallon</u>	<u>1984 \$/liter</u>
Variable Costs:		
Wood	\$0.807	\$0.213
Whey	0.176	0.046
Denaturant	0.040	0.011
Chemicals & Nutrients	0.310	0.082
Electricity	0.303	0.080
Other Variable Costs	0.003	0.001
	<hr/>	<hr/>
Subtotal	\$1.639	\$0.433
Fixed Costs:		
Direct Labor	\$0.424	0.112
Maintenance Materials	0.224	0.059
G&A	0.126	0.033
Other Fixed Costs	0.256	0.068
	<hr/>	<hr/>
Subtotal	\$1.030	\$0.272
	<hr/>	<hr/>
Total	\$2.669	\$0.705
Feed By-Product Credit	(0.271)	(0.072)
Electricity By-Product Credit	(0.920)	(0.243)
Capital-Related Charges	2.392	0.632
	<hr/>	<hr/>
REQUIRED SELLING PRICE	\$3.87	\$1.022

Basis: NYSERDA base case, 1988 figures deflated to 1984 dollars

- In enzyme production, efforts are needed to:
  - Confirm  $O_2$  and heat transfer requirements;
  - Determine the acceptability of media variations in use of silicone-based antifoams, phosphates, and surfactants.
- The fermentability of enzyme hydrolyzates needs confirmation.

There are numerous lower-priority needs with respect to development of a commercial, enzyme-based technology. Many of these relate to applications engineering (e.g., modifying equipment to convey solids aseptically). These issues must ultimately be resolved but are not generally crucial to the process economics. Examples of some of these needs are found in most areas of the process:

- In the pretreatment area, efficient steam recovery must be adequately demonstrated;
- The agitation requirements for hydrolysis vessels should be more thoroughly examined;
- Microaeration rates for the alcohol fermentation should be established;
- The fouling characteristics of the fermented beer should be examined to prevent problems with the distillation tower design;
- The degree of dewatering achievable for the T. reesei mycelia should be established; and
- Anaerobic digestion of the various waste streams should be evaluated and design parameters for waste treatment systems finalized.

It should be appreciated that this list of research needs is by no means exhaustive. The issues that have been identified are those which currently create the greatest concerns or have caused the conceptual design to be highly speculative. More refined problems will ultimately develop as the process continues its progression toward commercialization.

A final fact worth noting is that tackling these research needs one by one in separate laboratory or pilot projects will result in many sets of data which will be very difficult to relate to one another (similar to the existing literature today). Solving any one of these uncertainties will usually raise new questions about the effects on associated process areas. For this reason, perhaps the most pressing need is for the integrated operation over a significant time period of a flexible and well-designed pilot plant.

**The balance of this report may be requested from the  
Biofuels Information Center**